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AUTHOR(S):

Hui, Kin Ming

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Collapsing behaviour of the logarithmic diffusion equation

Kin Ming Hui

Institute of Mathematics, Academia Sinica,
Nankang, Taipei, 11529, Taiwan, R. O. C.

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Abstract

I will report my result on the collapsing behaviour of the maximal solution of the equation $u_t = \Delta \log u$ in $\mathbb{R}^2 \times (0, T)$, $u(x, 0) = u_0(x)$ in \mathbb{R}^2 , near its extinction time $T = \int_{\mathbb{R}^2} u_0 dx / 4\pi$ without using the Hamilton-Yau Harnack inequality. This result extends the recent result of P. Daskalopoulos, M.A. del Pino and N. Sesum [DP2], [DS2].

In this report I will discuss my recent result [Hu5] on the collapsing behaviour of the maximal solution of the logarithmic diffusion equation:

$$\begin{cases} u_t = \Delta \log u, u > 0, & \text{in } \mathbb{R}^2 \times (0, T) \\ u(x, 0) = u_0 & \text{in } \mathbb{R}^2. \end{cases} \quad (0.1)$$

(0.1) arises in many physical and geometric models. For example P.L. Lions and Toscani [LT] have shown that (0.1) arises as the diffusive limit for finite velocity Boltzmann kinetic models and T.G. Kurtz [Ku] has proved that (0.1) is the limiting density distribution of two gases moving against each other and obeying the Boltzmann equation. In [G] P.G. de Gennes showed that (0.1) also appears in the model of viscous liquid film lying on a solid surface and subjecting to long range Van der Waals interactions with fourth order term neglected.

Recently K.M. Hui [Hu3], [Hu4] (for the case $m > 0$ and $m < 0$), and J.R. Esteban, A. Rodriguez, J.L. Vazquez [ERV] (for the case $m > 0$) have shown that the solution of the porous medium equation

$$u_t = \Delta \left(\frac{u^m}{m} \right)$$

converges to the maximal solution of (0.1) as $m \rightarrow 0$. In [W1], [W2], [H], Angenent, L. Wu and R. Hamilton showed that the equation also arises in the study of the conformally equivalent metric $g_{ij} = u\delta_{ij}$ on \mathbb{R}^2 under the Ricci flow

$$\frac{\partial}{\partial t} g_{ij} = -2R_{ij} \quad (0.2)$$

where R_{ij} is the Ricci curvature of the metric g_{ij} . Note that in \mathbb{R}^2 the scalar curvature R is given by

$$R = -\frac{\Delta \log u}{u} \quad (0.3)$$

and the Ricci curvature is given by

$$R_{ij} = \frac{1}{2} R g_{ij}. \quad (0.4)$$

By (0.3) and (0.4) the Ricci flow equation (0.2) is equivalent to the logarithmic diffusion equation:

$$u_t = \Delta \log u.$$

1 Existence and properties of solutions

The equation (0.1) has many properties different from the heat equation such as existence of infinite many solutions for any given initial L^1 data. There also does not exist any fundamental solution for (0.1) [Hu1] which suggests that conservation of mass does not hold. K.M. Hui [Hu2] by using approximation by Neumann solutions in bounded domains and P. Daskalaopoulos and M.A.del Pino [DP1] by using approximation by Dirichlet solutions in bounded domains proved independently that corresponding to each

$$0 \leq u_0 \in L^p(\mathbb{R}^2) \cap L^1(\mathbb{R}^2), p > 1, 2 \leq f \in L^1(0, \infty),$$

there exists a classical solution u of (0.1) in $\mathbb{R}^n \times (0, T)$ satisfying the mass loss equation,

$$\int_{\mathbb{R}^2} u(x, t) dx = \int_{\mathbb{R}^2} u_0 dx - 2\pi \int_0^t f(s) ds \quad \forall 0 \leq t < T$$

where $T = T(u_0, f) > 0$ given by

$$\int_{\mathbb{R}^2} u_0 dx = 2\pi \int_0^T f(s) ds$$

is the extinction time for the solution u . Hence the solution with flux f vanishes identically to zero at time T .

Note that the maximal solution of (0.1) is the solution of (0.1) that corresponds to flux $f = 2$ which satisfies

$$\int_{\mathbb{R}^2} u(x, t) dx = \int_{\mathbb{R}^2} u_0 dx - 4\pi t \quad \forall 0 \leq t < T$$

with

$$T = \frac{1}{4\pi} \int_{\mathbb{R}^2} u_0 dx.$$

For any $2 < f \in C(0, T)$ the solution u with flux f satisfies the following decay condition at infinity:

$$\lim_{|x| \rightarrow \infty} \frac{\log u}{\log |x|} = -f \quad \text{uniformly on } [a, b] \quad \forall 0 < a < b < T$$

or equivalently

$$\lim_{|x| \rightarrow \infty} \frac{ru_r}{u} = -f \quad \text{uniformly on } [a, b] \quad \forall 0 < a < b < T.$$

One would like to ask what is the asymptotic behaviour of the solution with constant flux $f = \gamma \geq 2$? When $\gamma > 2$, S.Y. Hsu [Hs1], [Hs2], by using the lap number method of Matano [M], V.A. Galaktionov and L.A. Peletier [GP], proved that if the initial value is radially symmetric and monotone decreasing and u is the solution with flux $\gamma > 2$, then there exist unique constants $\alpha > 0$, $\beta > -1/2$, $\alpha = 2\beta + 1$, depending only on γ such that the rescaled function

$$v(y, s) = \frac{u(y/(T-t)^\beta, t)}{(T-t)^\alpha}, \quad s = -\log(T-t),$$

converges uniformly on every compact subset of \mathbb{R}^2 to $\phi_{\lambda, \beta}(y)$ for some constant $\lambda > 0$ as $s \rightarrow \infty$ where $\phi_{\lambda, \beta}(y) = \phi_{\lambda, \beta}(|y|)$ is radially symmetric and satisfies the following O.D.E.:

$$\frac{1}{r} \left(\frac{r\phi'}{\phi} \right)' + \alpha\phi + \beta r\phi' = 0 \quad \text{in } (0, \infty)$$

with

$$\phi(0) = 1/\lambda, \phi'(0) = 0.$$

In particular for $\gamma = 4$, the rescaled solution

$$v(x, s) = \frac{u(x, t)}{T-t}, \quad s = -\log(T-t),$$

converges uniformly on every compact subsets of \mathbb{R}^2 to the function

$$\frac{8\lambda}{(\lambda + |x|^2)^2}$$

as $s \rightarrow \infty$ for some constant $\lambda > 0$. What this said is that for solution with flux $f = 4$,

$$u(x, t) \approx \frac{8\lambda(T-t)}{(\lambda + |x|^2)^2} \quad \text{as } t \nearrow T$$

which corresponds to contracting spheres Ricci flow solution on S^2 .

What about the asymptotic behaviour of the solution with flux $f = 2$? J.R. King [K] by using inner and outer asymptotic expansion and matching asymptotic method showed that if u is the solution of the logarithmic diffusion equation (0.1) with flux $f = 2$ then as t approaches the extinction time T the vanishing behaviour for solution is very different from the vanishing behaviour for the case $f \equiv \gamma > 2$. J.R. King found that for compactly supportly finite mass initial value the maximal solution behaves like

$$\frac{(T-t)^2}{\frac{T}{2}|x|^2 + e^{\frac{2T}{T-t}}}$$

in the inner region $(T-t) \log |x| \leq T$ and behaves like

$$\frac{2t}{|x|^2(\log |x|)^2}$$

in the outer region $(T-t) \log |x| \geq T$ as $t \nearrow T$. In [DP2] P. Daskalopoulos and M.A. del Pino gave a rigorous proof of an extension of this formal result for radially symmetric initial value $u_0(r) \geq 0$ satisfying the conditions,

$$u_0(x) = u_0(|x|) \text{ is decreasing on } r = |x| \geq r_1 \text{ for some constant } r_1 > 0,$$

$$u_0(x) = \frac{2\mu}{|x|^2(\log |x|)^2}(1 + o(1)) \quad \text{as } |x| \rightarrow \infty,$$

for some constant $\mu > 0$ and

$$R_0(x) := -\frac{\Delta \log u_0}{u_0} \geq -\frac{1}{\mu} \quad \text{on } \mathbb{R}^2.$$

Later P. Daskalopoulos and N. Sesum [DS2] extended this result to the case of compactly supported $0 \leq u_0 \in L^1(\mathbb{R}^2) \cap L^\infty(\mathbb{R}^2)$. However their proof of the behaviour of the maximal solution in the outer region near the extinction time is very difficult and uses the Hamilton-Yau Harnack inequality. Recently in [Hu5] I extended their result to the case of initial value

$$0 \leq u_0 \in L^1(\mathbb{R}^2) \cap L^\infty(\mathbb{R}^2)$$

that satisfies

$$u_0(x) = u_0(|x|) \text{ is decreasing on } r = |x| \geq r_1 \text{ for some constant } r_1 > 0,$$

$$u_0(x) = \frac{2\mu}{|x|^2(\log|x|)^2}(1 + o(1)) \quad \text{as } |x| \rightarrow \infty,$$

and

$$R_0(x) := -\frac{\Delta \log u_0}{u_0} \geq -\frac{1}{\mu} \quad \text{on } \mathbb{R}^2$$

for some constant $\mu \geq 0$ with the right hand side being replaced by $-\infty$ if $\mu = 0$ and

$$\operatorname{ess\,inf}_{\bar{B}_{r_1}(0)} u_0 \geq \operatorname{ess\,sup}_{\mathbb{R}^2 \setminus B_{r_2}(0)} u_0 \quad \text{for some constant } r_2 > r_1. \quad (1.1)$$

Note that (1.1) is automatically satisfied if u_0 has compact support in \mathbb{R}^2 . In [Hu5] I proved the behaviour of the maximal solution in the outer region near the extinction time by elementary method without using the difficult Hamilton-Yau Harnack inequality for surfaces. I also obtained the behaviour of the maximal solution in the inner region as the extinction time is approached.

I will now assume that u_0 satisfies the above structural conditions and u is the maximal solution of (0.1) in $\mathbb{R}^2 \times (0, T)$ with flux $f \equiv 2$ and

$$T = \frac{1}{4\pi} \int_{\mathbb{R}^2} u_0 \, dx.$$

I will sketch of proof of [Hu5] here.

2 Inner region behaviour

By using the reflection method of D.G. Aronson and L.A. Caffarelli [AC] one has the following lemma:

Lemma 2.1. (*Lemma 1.1 of [Hu5]*) *The solution u satisfies*

$$u(x, t) \geq u(y, t)$$

for any $t \in (0, T)$ and $x, y \in \mathbb{R}^2$ such that $|y| \geq |x| + 2r_2$.

Then for any $0 < t < T$ there exists $x_t \in \bar{B}_{2r_2}$ such that

$$u(x_t, t) = \max_{x \in \mathbb{R}^2} u(x, t).$$

That is the maximum of $u(\cdot, t)$ is attained on the compact set \bar{B}_{2r_2} . We will now perform a rescaling of the solution of (0.1). Let

$$\bar{u}(x, \tau) = \tau^2 u(x, t), \quad \tau = \frac{1}{T-t}, \tau > 1/T.$$

Then \bar{u} satisfies

$$\bar{u}_\tau = \Delta \log \bar{u} + \frac{2\bar{u}}{\tau} \quad \text{in } \mathbb{R}^2 \times (1/T, \infty).$$

Let

$$R_{\max}(t) = \max_{x \in \mathbb{R}^2} R(x, t)$$

and let $W(t)$ be the width function with respect to the metric $g_{ij}(t)$ as defined by P. Daskalopoulos and R. Hamilton [DH]. We now recall a result of P. Daskalopoulos and R. Hamilton [DH]:

Theorem 2.2. ([DH]) *There exist positive constants $c > 0$ and $C > 0$ such that*

$$(i) \quad c(T - t) \leq W(t) \leq C(T - t)$$

$$(ii) \quad \frac{c}{(T-t)^2} \leq R_{\max}(t) \leq \frac{C}{(T-t)^2}$$

hold for any $0 < t < T$.

By Theorem 2.2,

$$c \leq \limsup_{t \nearrow T} (T - t)^2 R_{\max}(t) \leq C.$$

Hence the singularity is a type II singularity. Note that u satisfies the Aronson-Bénilan inequality,

$$\frac{u_t}{u} \leq \frac{1}{t} \quad \text{in } \mathbb{R}^2 \times (0, T).$$

As

$$R = -\frac{\Delta \log u}{u} = -\frac{u_t}{u},$$

the Aronson-Bénilan inequality is equivalent to

$$R \geq -\frac{1}{t}.$$

So if we let

$$\bar{R}(x, \tau) = -\frac{\Delta \log \bar{u}}{\bar{u}}.$$

Then

$$\frac{2}{\tau} + \frac{2}{\tau^2 T} \geq \frac{\bar{u}_\tau}{\bar{u}} \geq -C \quad \text{in } \mathbb{R}^2 \times (2/T, \infty). \quad (2.1)$$

Theorem 2.3. (Theorem 1.3 of [Hu5]) *For any sequence $\{\tau_k\}_{k=1}^\infty$, $\tau_k \rightarrow \infty$ as $k \rightarrow \infty$, let*

$$\bar{u}_k(y, \tau) = \alpha_k \bar{u}(\alpha_k^{\frac{1}{2}} y + x_{t_k}, \tau + \tau_k), \quad y \in \mathbb{R}^2, \tau > -\tau_k + T^{-1}$$

where

$$t_k = T - \tau_k^{-1} \quad \forall k \in \mathbb{Z}^+$$

and

$$\alpha_k = 1/\bar{u}(x_{t_k}, \tau_k).$$

Then $\{\bar{u}_k\}_{k=1}^\infty$ has a subsequence $\{\bar{u}_{k_i}\}_{i=1}^\infty$ that converges uniformly on $C^\infty(K)$ for any compact set $K \subset \mathbb{R}^2 \times (-\infty, \infty)$ as $i \rightarrow \infty$ to a positive solution

$$U(y, \tau) = \frac{1}{\lambda|y|^2 + e^{4\lambda\tau}}.$$

of equation

$$U_\tau = \Delta \log U \quad \text{in } \mathbb{R}^2 \times (-\infty, \infty)$$

with uniformly bounded non-negative scalar curvature and uniformly bounded width on $\mathbb{R}^2 \times (-\infty, \infty)$ with respect to the metric $\tilde{g}_{ij}(t) = U(\cdot, t)\delta_{ij}$ where $\lambda > 0$ is some constant.

Proof:(Sketch) By definition,

$$\bar{u}_k(0, 0) = 1 \quad \text{and} \quad \bar{u}_k(y, 0) \leq 1 \quad \forall y \in \mathbb{R}^2.$$

Let $a < b$. By (2.1) there exist constants $M_1 > 0$ and $k_0 \in \mathbb{Z}^+$ such that

$$\bar{u}_k(x, \tau) \leq M_1 \quad \text{and} \quad |\bar{u}_{k,\tau}(x, \tau)| \leq CM_1 \quad x \in \mathbb{R}^2, a \leq \tau \leq b, k \geq k_0. \quad (2.2)$$

By (2.2) one can deduce the following Harnack inequality:

For any $R_1 > 0$, $a < b$, there exists a constant $C_2 > 0$ such that

$$\sup_{\substack{|y| \leq R_1 \\ a \leq \tau_1 \leq b}} \bar{u}_k(y, \tau_1)^9 \leq C_2 \inf_{\substack{|x| \leq R_1 \\ a \leq \tau_2 \leq b}} \bar{u}_k(x, \tau_2) \quad \forall k \geq k_0.$$

Hence the sequence \bar{u}_k is uniformly parabolic on $\bar{B}_{R_1} \times [a, b]$ and are uniformly Holder continuous in $C^{2\gamma, 1\gamma}(\bar{B}_{R_1} \times [a, b])$ for any $\gamma \in \mathbb{Z}^+$. Then the sequence $\{\bar{u}_k\}_{k=1}^\infty$ has a subsequence which we may assume without loss of generality to be the sequence itself that converges uniformly in $C^\infty(K)$ as $k \rightarrow \infty$ for any compact set $K \subset \mathbb{R}^2 \times (-\infty, \infty)$ to some positive function U that satisfies the logarithmic diffusion equation. Let

$$\bar{R}_k = -\frac{\Delta \log \bar{u}_k}{\bar{u}_k}.$$

Then \bar{R}_k converges uniformly on every compact subset of $\mathbb{R}^2 \times (-\infty, \infty)$ as $k \rightarrow \infty$ to the scalar curvature

$$\bar{R} = -\frac{\Delta \log U}{U}$$

of the metric $\tilde{g}_{ij}(\tau) = U(\cdot, \tau)\delta_{ij}$. Moreover

$$0 \leq \bar{R}(y, \tau) \leq C \quad \forall (y, \tau) \in \mathbb{R}^2 \times (-\infty, \infty).$$

By an approximation argument the width function with respect to the metric $\widetilde{g}_{ij}(\tau) = U(\cdot, \tau)\delta_{ij}$ is uniformly bounded on $\mathbb{R}^2 \times (-\infty, \infty)$. Then by the result of P. Daskalopoulos and N. Sesum [DS1],

$$U(y, \tau) = \frac{2}{\beta(|y - y_0|^2 + \delta e^{2\beta\tau})}$$

for some $y_0 \in \mathbb{R}^2$ and constants $\beta > 0$, $\delta > 0$. Since $\bar{u}_k(y, 0)$ attains its maximum at $y = 0$, $U(y, 0)$ will attain its maximum at $y = 0$. Hence $y_0 = 0$.

$$U(0, 0) = 1 \quad \Rightarrow \quad 1 = \frac{2}{\beta\delta}.$$

Thus

$$U(y, \tau) = \frac{1}{\lambda|y|^2 + e^{4\lambda\tau}}.$$

for some constant $\lambda > 0$. □

It can be proved that

$$\alpha_k \rightarrow \infty \quad \text{as } k \rightarrow \infty$$

Hence we can change the origin in rescaling and have the following result:

Lemma 2.4. (*Lemma 1.10 of [Hu5]*) *Let*

$$q_k(y, \tau) = \alpha_k \bar{u}(\alpha_k^{\frac{1}{2}} y, \tau + \tau_k).$$

Then $q_{k_i}(y, \tau)$ converges uniformly in $C^\infty(K)$ for every compact set $K \subset \mathbb{R}^2$ to the function $U(y, \tau)$ as $\tau \rightarrow \infty$.

We will now perform a change of scaling. Let

$$\beta(\tau) = 1/\bar{u}(0, \tau),$$

$\beta_k = \beta(\tau_k)$, and

$$\bar{q}_k(y, \tau) = \beta_k \bar{u}(\beta_k^{\frac{1}{2}} y, \tau + \tau_k).$$

Then

$$\frac{\alpha_k}{\beta_k} = q_k(0, 0) \rightarrow U(0, 0) = 1 \quad \text{as } k \rightarrow \infty.$$

Hence there exists $k_0 \in \mathbb{Z}^+$ and constants $c_2 > c_1 > 0$ such that

$$c_1 \leq \frac{\beta_k}{\alpha_k} \leq c_2 \quad \forall k \geq k_0.$$

Thus we have the following result.

Theorem 2.5. (Theorem 1.11 of [Hu5]) \bar{q}_k has a subsequence \bar{q}_{k_i} that converges uniformly on $C^\infty(K)$ for any compact set $K \subset \mathbb{R}^2 \times (-\infty, \infty)$ to $U(y, \tau)$ as $\tau \rightarrow \infty$. Moreover $\beta_k \rightarrow \infty$ as $k \rightarrow \infty$.

Lemma 2.6. (Proposition 1.17 and Proposition 1.18 of [Hu5])

$$\lim_{\tau \rightarrow \infty} \frac{\beta'(\tau)}{\beta(\tau)} = \lim_{\tau \rightarrow \infty} \frac{\log \beta(\tau)}{\tau} = 2(T + \mu).$$

Let

$$\tilde{R}_k = -\frac{\Delta \log \bar{q}_k}{\bar{q}_k}.$$

Since

$$\tilde{R}_k(0, 0) = \frac{\beta'(\tau_k)}{\beta(\tau_k)} + \frac{2}{\tau_k},$$

then

$$4\lambda = \lim_{\tau \rightarrow \infty} \tilde{R}_k(0, 0) = 2(T + \mu).$$

Let

$$\bar{q}(y, \tau) = \beta(\tau) \bar{u}(\beta(\tau)^{\frac{1}{2}} y, \tau).$$

We then have the following main theorem for inner region.

Theorem 2.7. (Theorem 1.21 of [Hu5]) $\bar{q}(y, \tau)$ converges uniformly on $C^\infty(K)$ for any compact set $K \subset \mathbb{R}^2$ to the function

$$U_\mu(y) = \frac{1}{\frac{(T+\mu)}{2}|y|^2 + 1}$$

as $\tau \rightarrow \infty$.

Corollary 2.8. (cf. [Hu5]) For any $\varepsilon > 0$ and $M > 0$ there exist $\tau_0 > 1/T$ and $C > 0$ such that

$$\begin{cases} \left| u(x, t) - \frac{(T-t)^2}{\lambda|x|^2 + \beta(\tau)} \right| < u(0, t)\varepsilon & \forall |x| \leq \beta(\tau)^{\frac{1}{2}}M, \tau > \tau_0 \\ u(0, t) \leq C(T-t)^2 & \forall t > T - \tau_0^{-1}. \end{cases}$$

where $\tau = 1/(T-t)$.

As in [DP2], [DS2], [Hu5], we now consider the cylindrical change of variables,

$$v(\zeta, \theta, t) = r^2 u(r, \theta, t), \quad \zeta = \log r, r = |x|$$

and let

$$\bar{v}(\xi, \theta, \tau) = \tau^2 v(\tau \xi, \theta, t), \quad \tau = 1/(T-t), \tau \geq 1/T.$$

Then \bar{v} satisfies

$$\tau \bar{v}_\tau = \frac{1}{\tau} (\log \bar{v})_{\xi\xi} + \tau (\log \bar{v})_{\theta\theta} + \xi \bar{v}_\xi + 2\bar{v} \quad \text{in } \mathbb{R} \times [0, 2\pi] \times (1/T, \infty).$$

Corollary 2.9. (Lemma 1.23 of [Hu5]) For any $\varepsilon > 0$ there exists $\tau_0 > 1/T$ such that

$$\left| \widetilde{v}(\xi, \theta, \tau) - \frac{e^{2\tau\xi}}{\frac{T+\mu}{2}e^{2\tau\xi} + \beta(\tau)} \right| < \frac{e^{2\tau\xi}}{\beta(\tau)} \varepsilon \quad \forall \xi \leq \frac{\log \beta(\tau)}{2\tau}, \theta \in [0, 2\pi], \tau \geq \tau_0.$$

Corollary 2.10. (Corollary 1.24 of [Hu5])

$$\int_{-\infty}^{\xi^-} \int_0^{2\pi} \widetilde{v}(\xi, \theta, \tau) d\theta d\xi \rightarrow 0 \quad \text{as } \tau \rightarrow \infty$$

and

$$\lim_{\tau \rightarrow \infty} \widetilde{v}(\xi, \theta, \tau) = 0 \quad \text{uniformly on } (-\infty, \xi^-] \times [0, 2\pi]$$

for any $\xi^- < T + \mu$.

3 Outer region behaviour

Let

$$\xi(\tau) = (\log \beta(\tau))/2\tau.$$

Lemma 3.1. (Lemma 2.1 of [Hu5]) There exists constants $C_1 > 0$, $C_2 > 0$, $C_3 > 0$ and $\tau_0 > 1/T$ such that the following holds.

- (i) $\widetilde{v}(\xi, \theta, \tau) \leq C_1 \quad \forall \xi \in \mathbb{R}, \theta \in [0, 2\pi], \tau \geq 1/T$
- (ii) $\widetilde{v}(\xi, \theta, \tau) \geq \frac{C_2}{\xi^2} \quad \forall \xi \geq \xi(\tau), \theta \in [0, 2\pi], \tau \geq \tau_0$
- (iii) $\widetilde{v}(\xi, \theta, \tau) \leq \frac{C_3}{\xi^2} \quad \forall \xi > 0, \theta \in [0, 2\pi], \tau \geq \tau_0.$

Moreover

$$\xi(\tau) = T + \mu + o(1) \quad \text{as } \tau \rightarrow \infty.$$

We now let

$$w(\xi, \theta, s) = \widetilde{v}(\xi, \theta, \tau)$$

with

$$s = \log \tau = -\log(T - t).$$

Then

$$w_s = e^{-s}(\log w)_{\xi\xi} + e^s(\log w)_{\theta\theta} + \xi w_\xi + 2w \quad \text{in } \mathbb{R} \times [0, 2\pi] \times (-\log T, \infty).$$

The following is the main theorem for outer region.

Theorem 3.2. (Theorem 2.3 of [Hu5]) As $\tau \rightarrow \infty$, the function \tilde{v} converges to the function

$$V(\xi) = \begin{cases} \frac{2(T+\mu)}{\xi^2} & \forall \xi > T + \mu \\ 0 & \forall \xi < T + \mu. \end{cases}$$

Moreover the convergence is uniform on $(-\infty, a]$ for any $a < T + \mu$ and on $[\xi_0, \xi'_0]$ for any $\xi'_0 > \xi_0 > T + \mu$.

Proof:(Sketch) Let $\{s_k\}_{k=1}^\infty$ be a sequence such that $s_k \rightarrow \infty$ as $k \rightarrow \infty$ and

$$w_k(\xi, \theta, s) = w(\xi, \theta, s + s_k) \quad \forall \xi \in \mathbb{R}, 0 \leq \theta \leq 2\pi, s \geq -\log T - s_k.$$

Let

$$W_k^b(\eta, s) = \int_\eta^b \int_0^{2\pi} w_k(\xi, \theta, s) d\theta d\xi \quad \forall b \geq \eta > T + \mu, s > -\log T - s_k, k \in \mathbb{Z}^+,$$

$$W_k(\eta, s) = \int_\eta^\infty \int_0^{2\pi} w_k(\xi, \theta, s) d\theta d\xi \quad \forall \eta > T + \mu, s > -\log T - s_k, k \in \mathbb{Z}^+$$

and let $\{b_i\}_{i=1}^\infty$ be a monotonically increasing sequence such that $b_i > T + \mu$ for any $i \in \mathbb{Z}^+$ and $b_i \rightarrow \infty$ as $i \rightarrow \infty$.

Since

$$\begin{aligned} \int_{\mathbb{R}^2} u(x, t) dx &= 4\pi(T - t) \quad \forall 0 < t < T, \\ \int_{-\infty}^\infty \int_0^{2\pi} w_k(\xi, \theta, s) d\theta d\xi &= 4\pi \quad \forall s > -\log T - s_k, k \in \mathbb{Z}^+. \end{aligned}$$

One can prove that there exists a function \bar{w} and a subsequence of \mathbb{Z}^+ which we may assume without loss of generality to be \mathbb{Z}^+ itself such that

$$W_k^{b_i} \rightarrow W^{b_i} \quad \text{uniformly on } [a, b] \times [c, d] \quad b > a > T + \mu, d > c \quad \text{as } k \rightarrow \infty$$

for any $i \in \mathbb{Z}^+$ and

$$W_k \rightarrow W \quad \text{uniformly on } [a, b] \times [c, d] \quad b > a > T + \mu, d > c \quad \text{as } k \rightarrow \infty$$

where

$$W^b(\eta, s) = \int_\eta^b \int_0^{2\pi} \bar{w}(\xi, \theta, s) d\theta d\xi, \quad W(\eta, s) = \int_\eta^\infty \int_0^{2\pi} \bar{w}(\xi, \theta, s) d\theta d\xi.$$

By elementary argument one can show that

$$\eta W(\eta, s) = \bar{\eta} W(\bar{\eta}, \bar{s}) \quad \forall \eta, \bar{\eta} > T + \mu, s, \bar{s} \in \mathbb{R}$$

and

$$W(T + \mu, s) = 4\pi \quad \forall s \in \mathbb{R}.$$

Letting $\bar{\eta} \rightarrow T + \mu$,

$$W(\eta, s) = \frac{4\pi(T + \mu)}{\eta} \quad \forall \eta > T + \mu, s \in \mathbb{R}$$

which will then imply the theorem after some elementary computation. \square

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